A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
06 (02.01.2; 08.02.1; 08.09.02; 13.25.5)

ASTRONOMY
AND
ASTROPHYSICS
26.9.1995

Low-frequency QPO in the X-ray transient GRO J1719–24

F. van der Hooft[1], C. Kouveliotou[2,3], J. van Paradijs[1,4], B. C. Rubin[2,3], D. J. Crary[3,5], M. H. Finger[2,3], B. A. Harmon[3], M. van der Klis[1], W. H. G. Lewin[6], J. P. Norris[7], and G. J. Fishman[3]

[1] Astronomical Institute "Anton Pannekoek", University of Amsterdam and Center for High Energy Astrophysics, Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands
[2] Universities Space Research Association, Huntsville, AL 35806, USA
[3] NASA/Marshall Space Flight Center, Huntsville, AL 35812, USA
[4] Department of Physics, University of Alabama in Huntsville, Huntsville, AL 35899, USA
[5] NAS/NRC Research Associate, NASA Code ES-84, Marshall Space Flight Center, Huntsville, AL 35812, USA
[6] Massachusetts Institute of Technology, 37-627 Cambridge, MA 02139, USA
[7] NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

NASA-TM-111447

Received date; accepted date

Abstract. We present the results of an analysis of the time variability of the soft X-ray transient GRO J1719–24 (Nova Oph 1993) as observed with BATSE. Our analysis covers the entire $\sim$ 80 day outburst, beginning with the first detection on September 25, 1993. We obtained power density spectra (PDS) of the data in the 20–100 keV energy band covering the frequency interval 0.002–0.488 Hz. The PDS show a significant QPO peak whose centroid frequency increased from $\sim$ 0.04 Hz at the onset of the outburst, to $\sim$ 0.3 Hz at the end. Additional noise is present in the PDS which we describe in terms of two components. We find that the evolution of the PDS can be described as a gradual stretching by a factor $\sim$ 7.5 in frequency of the power spectrum.

Key words: Accretion, accretions disks – *(Stars:)* binaries: close, individual: GRO J1719–24 – X-rays: stars

1. Introduction

During the last decade, the Burst And Transient Source Experiment (BATSE) on board of the Compton Gamma Ray Observatory, and the SIGMA telescope on board GRANAT have discovered and monitored several X-ray transient sources, e.g. GS 1124–68/Nova Mus 1991 (Makino et al. 1991, Lund & Brandt 1991), GRO J0422+34/Nova Per 1992 (Paciesas et al. 1992), GRS 1009–45/Nova Vel 1993 (Lapshov, Sazonov, & Sunyaev 1993, Harmon et al. 1993a) and GRO J1655–40/Nova Sco 1994 (Zhang et al. 1994).

Soft X-ray transients are characterized by a sudden increase in X-ray luminosity, reaching a maximum X-ray brightness usually within a few days, and a subsequent decay of the X-ray flux over a period of months. They are low-mass X-ray binaries (LMXBs), and most of them are believed to contain a stellar-mass black-hole as the compact object. So far, six X-ray transients are dynamically proven black-hole candidates (BHCs) [A0620–00 (McClintock & Remillard 1986), GS 2023+338 (Casares, Charles & Naylor 1992), GS 1124–68 (Remillard, McClintock & Bailyn 1992), GRO J0422+32 (Orosz & Bailyn 1994), GRO J1655–40 (Bailyn & Orosz 1995) and GS 2000+25 (Charles & Casares 1995)]. Several other transients are regarded as BHCs, based on the presence of a hard spectral component in the > 20 keV range extending up to a few hundred keV, with a typical photon index in the range 1.4–2.5 often considered to be the signature of an accreting black-hole (Sunyaev et al. 1991, Tanaka & Lewin 1995; see however, van Paradijs & van der Klis 1994) and rapid X-ray variability similar to that seen in the dynamically proven BHCs (van der Klis 1995a). In this letter we report on the temporal analysis of data obtained with BATSE of the X-ray transient GRO J1719–24.

2. Observations

GRO J1719–24 (= GRS 1716–249, Nova Oph 1993) was detected independently with BATSE and the SIGMA telescope on GRANAT on September 25, 1993 (Ballet et al. 1993, Harmon et al. 1993b). The source reached a maximum flux of $\sim$ 1.4 Crab (20–100 keV) on September 30. After the initial rise the source brightness remained remarkably constant, with an average flux decrease in the period October 1 – November 22, 1993 of only $\sim$ 15 % (Harmon et al. 1993c). From December 9 (day 75 of the outburst) the 20–100 keV flux of GRO J1719–24 suddenly decreased within six days from 1.1 ± 0.1 to 0.4 ± 0.0[illegible]

Send offprint requests to: F. van der Hooft

Crab, and on December 16–18 it went below the BATSE 3σ 1-day detection limit of 0.1 Crab (Harmon & Paciesas 1993). The X-ray lightcurve, based on Earth occultation measurements (Harmon et al. 1993d), is shown in Figure 1. After this outburst, GRO J1719–24 remained undetectable for BATSE until September 1994, when it was detected with both SIGMA (Churazov et al. 1994) and BATSE (Harmon et al. 1994). This later period of activity is not discussed here.

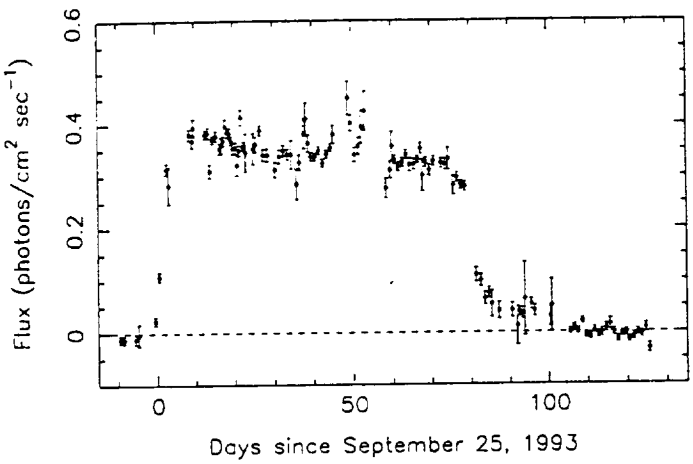

Fig. 1. Flux history of GRO J1719–24 in the 20–100 keV energy band. The first detection of the source was made on September 25, 1993, and it reached a maximum flux of ~ 1.4 Crab in six days. After 70 days at a slowly decreasing, high flux level, the source exhibited a rapid decrease of the flux and became undetectable by BATSE after 83 days.

3. Time series analysis

BATSE consists of eight identical detector modules, each with a Large Area Detector (LAD) and a spectroscopy detector. The LADs are oriented such that their normal vectors are perpendicular to the faces of a regular octahedron; BATSE functions as an all-sky monitor in the hard X-ray/gamma-ray energy band. We have used 1.024 s time resolution count rate data from the large area detectors (four broad energy channels) and applied an empirical model (Rubin et al. 1995) to subtract the signal due to the X-ray/gamma-ray background. This model describes the background by a harmonic expansion in orbital phase (with parameters determined from the observed background variations), and includes the risings and settings of the brightest X-ray sources in the sky. It uses eight orbital harmonic terms, and its parameters were updated every three hours.

For our analysis, we considered uninterrupted data segments of 512 successive time bins (of 1.024 s each) on which we performed Fast Fourier Transforms (FFTs) covering the frequency interval 0.002–0.488 Hz. We obtained typically 35 of such segments per day while the source was above the Earth horizon. For each data segment and for each of the eight detectors separately, we calculated and coherently summed the FFTs of the 20–50 and 50–100 keV energy channels. We used only those detectors which had the source within 60 degrees of the normal; their FFTs were weighted by the ratio of the source to the total count rates again summed coherently and converted to Power Density Spectra (PDS). The PDS were normalized such that the power density is given in units of (rms/mean)^2 Hz^{-1} (see e.g. van der Klis 1995b) and finally averaged over an entire day.

The PDS show a significant peak, indicative of quasi-periodic oscillations (QPO) in the time series. The centroid frequency of this peak slowly shifts towards higher frequencies; the centroid frequency of the QPO doubled from ~ 0.04 to ~ 0.08 Hz during the rise to maximum flux, and then gradually increased to ~ 0.3 Hz. The QPO are absent when the flux starts rapidly decaying at day 75. The PDS rise below ~ 0.01 Hz; this is unlikely to be caused by the source, since it also appears in the PDS obtained while GRO J1719–24 was occulted by the Earth. Therefore, we excluded the frequency range below 0.01 Hz from the analysis.

Careful inspection of the PDS, ordered in a grey-scale coded time sequence (see van der Hooft et al. 1995) revealed the presence of structure on each side of the QPO peak. The position of these additional structures seemed to scale with the frequency of the QPO. To further investigate this, we made fits to the PDS using a combination of a power law and three Lorentzian profiles. To improve statistics, we made fits to the average PDS of 3 consecutive days, obtaining 23 3-day averaged PDS. The model required 11 parameters (3 for each Lorentzian, 2 for the power law) to be determined, which left 23 degrees of freedom (the PDS were logarithmically rebinned to 34 frequency bins). Reduced χ^2 values of the fits were between 0.6 and 2.2. For the fit to the 3-day averaged PDS starting at days 61 and 70 we used a combination of a power law and two Lorentzian profiles only, since the noise component at the highest frequency is no longer well defined as it reaches the Nyquist frequency. The centroid frequencies of the three Lorentzian profiles (ν_1, ν_2 and ν_3, in order of increasing frequency), are strongly correlated (see Figure 2).

Over a wide frequency interval, the centroid frequencies of the QPO and the two noise components are consistent with being linearly related. We applied fits of the form $\nu_i = A + B\,\nu_j$ (taking the errors in both ν_i and ν_j into account, see e.g. Press et al. 1992) to the data points, also shown in Fig. 2. The parameters of these fits are tabulated in Table 1. A linear fit offers a good description of the data, resulting in a reduced χ^2 of 2.5 and 0.68 for the fits to (ν_1, ν_2) and (ν_2, ν_3), respectively. When extrapolated, both fits go through the origin, which indicates that the frequencies indeed scale with a single factor. Therefore, we attempted a second serie of fits, this time forced to pass the origin by setting $A \equiv 0$. This resulted also in acceptable fits (shown as a dashed line in Fig. 2) and a more precise determination of the slope. Based on this last series of fits, we find that there is no significant difference between the frequency ratios (ν_1/ν_2) and (ν_2/ν_3); we can exclude that these ratios have integer values.

This result led to the hypothesis that the PDS during the outburst of GRO J1719–24 may be described with a single

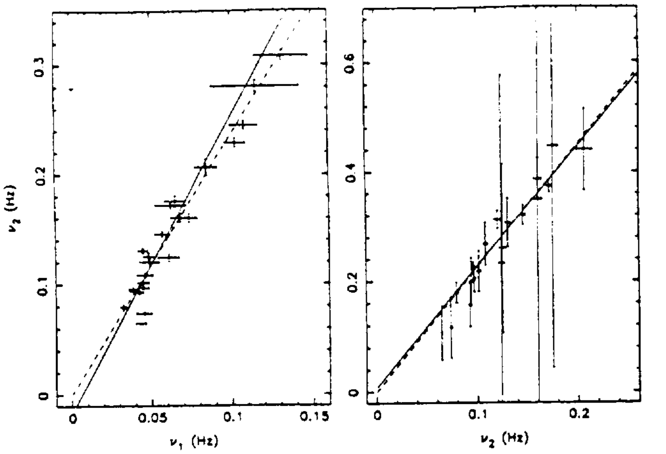

Fig. 2. Values of the centroid frequencies of the three Lorentzian profiles, plotted versus each other. The left panel contains (ν_1, ν_2) and covers day 4–72, the right panel contains (ν_2, ν_3) and covers day 4–60. Also, a fit of the form $\nu_i = A + B\,\nu_j$ is shown, with its parameters listed in Table 1. The dashed line represents the fit which is forced to pass the origin.

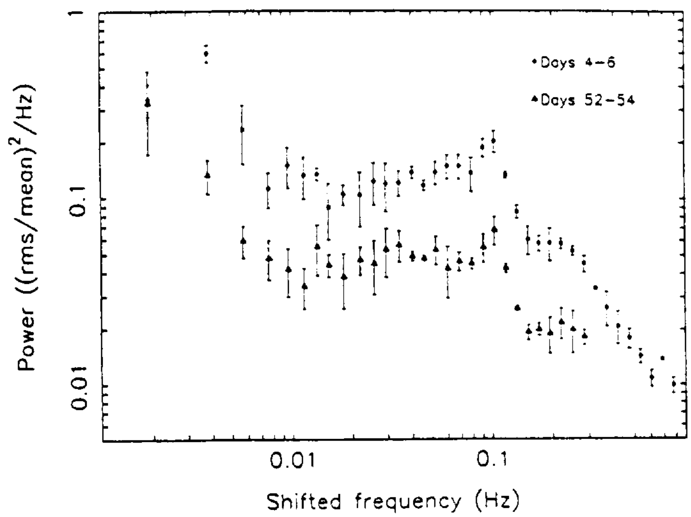

Fig. 3. Nine-day averaged PDS (starting at days 4 and 52, respectively) rescaled in frequency by such factors that the centroid frequency of the QPO became equal to 0.1 Hz. The relative stretch factor of these two spectra is 3.2.

Table 1. Parameters of fits shown in Fig. 2.

	A	B	N^a	$\chi^2_{\rm red}$
(ν_1, ν_2)	-0.017 ± 0.008	2.70 ± 0.16	23	2.5
(ν_1, ν_3)	-0.036 ± 0.042	6.13 ± 0.91	19	1.2
(ν_2, ν_3)	0.008 ± 0.022	2.19 ± 0.18	19	0.68
(ν_1, ν_2)	0.0	2.363 ± 0.041	23	2.6
(ν_1, ν_3)	0.0	5.40 ± 0.19	19	1.2
(ν_2, ν_3)	0.0	2.257 ± 0.048	19	0.64

[a] Indicates the number of data points.

characteristic profile whose frequency scale stretched proportionally like an accordeon. To test this hypothesis, we scaled each power spectrum in frequency by a factor such that the centroid frequency ν_2 of the QPO peak became equal to 0.1 Hz. Two such frequency scaled PDS are shown in Figure 3. It is evident that their shapes are very similar. The relative stretch factor of these two spectra is as large as 3.2.

4. Discussion

Soon after the X-ray detection of GRO J1719–24, a possible optical counterpart was discovered (Della Valle, Mirabel & Rodriquez 1994), whose photometric and spectroscopic properties suggest that GRO J1719–24 is an LMXB. Since the orbital period and mass function of the system are not yet determined, GRO J1719–24 is still regarded as a BHC based on its hard energy spectrum only.

Low-frequency (0.04–0.8 Hz) QPO have been observed in the BHCs Cyg X-1, LMC X-1, GX 339–4 and GRO J0422+32 (van der Klis 1995a). These QPO were observed while the sources were in their so-called low state, with the exception of LMC X-1 where a 0.08 Hz QPO was found while an ultra-soft component dominated the energy spectrum, showing that the source was in the high state. The large variation in QPO frequency seen in this source gives support to the idea that all low-frequency ($\lesssim$ 1 Hz) QPO in BHCs have the same origin. It is important to mention that the intermediate frequency QPO in GX 339–4 (6 Hz, Miyamoto et al. 1991) and GS 1124–68 (3–10 Hz, Miyamoto et al. 1993) occurred while these sources were in the very high state.

In spite of the large range in frequency of the QPO, the PDS of GRO J1719–24 obey a remarkable regularity; their shape, after introducing a frequency scaling factor, does not appear to change much. This is reminiscent of the time-scale invariance of the type II burst profiles of the Rapid Burster (Lewin et al. 1995), which harbours a neutron star (Hofmann et al. 1978). If these phenomena are related, this would imply that the mechanism responsible for the $\lesssim$ 1 Hz QPO is not unique to BHCs.

Since the dynamical time scale in the inner region of a disk surrounding a stellar-mass black hole is is in the millisecond range, the QPO in GRO J1719–24 may have an origin further out in the disk. The inner regions of viscous accretion disks surrounding black holes may suffer thermal-viscous instabilities when radiation pressure is important (Piran 1978). Chen & Taam (1994) have recently suggested that low-frequency QPO ($\sim$ 0.04 Hz) in BHCs may be explicable by such thermal-viscous instabilities. A general property of this disk instability is that the frequency of the oscillation is a function of $\dot{M}$. Assuming a direct relation between source intensity and $\dot{M}$, one would expect that the frequency increases when the intensity decreases (Chen & Taam 1994). In GRO J1719–24 the QPO frequency increased by a factor 7.5 while the 20–100 keV flux decreased by only 20 %; it is not clear whether such a large change in QPO frequency for such a small change in $\dot{M}$ can be explained by the thermal-viscous model.

Acknowledgements. FvdH acknowledges support by the Netherlands Foundation for Research in Astronomy with financial aid from the Netherlands Organisation for Scientific Research (NWO) under contract number 782-376-011. FvdH also thanks the "Leids Kerkhoven–Bosscha Fonds" for a travel grant. JvP acknowledges support from NASA NAG5-2560. WHGL was supported by NASA grant NAG8-216. This project was supported in part by NWO under grant PGS 78-277.

References

Bailyn, C., & Orosz, J. 1995, IAU Circ., 6173
Ballet, J., Denis, M., Gilfanov, M., & Sunyaev, R. 1993, IAU Circ., 5874
Belloni, T., & Hasinger, G. 1990, A&A, 230, 103
Casares, J., Charles, P., & Naylor, T. 1992, Nat., 355, 614
Charles, P., & Casares, J. 1995, IAU Circ., 6193
Chen, X., & Taam, R. E. 1994, ApJ, 431, 732
Churazov, E., Gilfanov, M., Ballet, J., & Jourdain, E. 1994, IAU Circ., 6083
Della Valle, M., Mirabel, I. F., & Rodriquez, L. F. 1994, A&A, 290, 803
Harmon, B. A., Zhang, S. N., Fishman, G. J., & Paciesas, W. S. 1993a, IAU Circ., 5864
Harmon, B. A., Zhang, S. N., Paciesas, W. S., & Fishman, G. J. 1993b, IAU Circ., 5874
Harmon, B. A., Fishman, G. J., Paciesas, W. S., & Zhang, S. N. 1993c, IAU Circ., 5900
Harmon, B. A., et al. 1993d, AIP Conf. Proc. 280, "1st Compton Gamma Ray Observatory Symp.", eds. M. Friedlander, N. Gehrels & D. Macomb (New York: AIP), 345
Harmon, B. A., & Paciesas, W. S. 1993, IAU Circ., 5913
Harmon, B. A., Zhang, S. N., Paciesas, W. S., Wilson, C. A., & Fishman, G. J. 1994, IAU Circ., 6104
Hoffman, J. A., Marshall, H. L., & Lewin, W. H. G. 1978, Nat, 271, 630
Lapshov, I., Sazonov, S., & Sunyaev, R. 1993, IAU Circ., 5864
Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1995, in: X-ray Binaries, eds. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge University Press), 175
Lund, N., & Brandt, S. 1991, IAU Circ., 5161
Makino, F., et al. 1991, IAU Circ., 5161
Miyamoto, S., Kimura, K., Kitamoto, S., Dotani, T., & Ebisawa, K. 1991, ApJ, 383, 784
Miyamoto, S., Iga, S., Kitamoto, S., & Kamado, Y. 1991, ApJ, 403, L39
McClintock, J., & Remillard, R. 1986, ApJ, 308, 110
Orosz, J., & Bailyn, C. 1994, IAU Circ., 6103
Paciesas, W. S., Briggs, M. S., Harmon, B. A., Wilson, R. B., & Finger, M. H. 1992, IAU Circ., 5580
Piran, T. 1978, ApJ, 221, 625
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes (Cambridge: Cambridge University Press)
Remillard, R., McClintock, J., & Bailyn, C. 1992, ApJ, 399, L145
Rubin, B. C., et al. 1995, in preparation
Sunyaev, R., et al. 1991, A&A, 247, L29
Tanaka, Y., & Lewin, W. H. G. 1995, in: X-ray Binaries, eds. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge University Press) p. 126
van Paradijs, J., & van der Klis, M. 1994, A&A, 281, L17
van der Hooft, F., et al. 1995, in preparation
van der Klis, M. 1995a, in: X-ray Binaries, eds. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge University Press), 252
van der Klis, M. 1995b, in: The lives of the neutron stars, eds. M. A. Alpar, Ü. Kiziloğlu, & J. van Paradijs (Dordrecht: Kluwer Academic Publishers), 301
Zhang, S. N., et al. 1994, IAU Circ., 6046